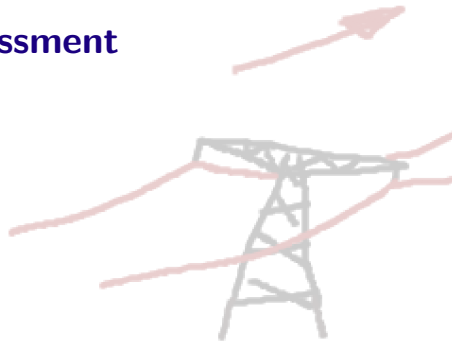
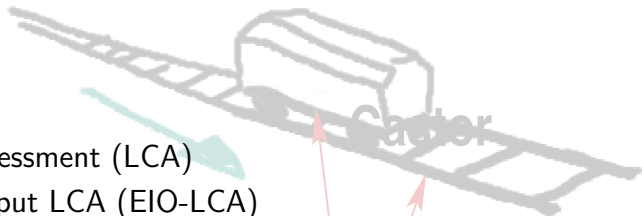


13 Life-Cycle Assessment

~~CO₂~~



- ▶ 13.1. Classical Life-Cycle Assessment (LCA)
- ▶ 13.2. Econometric Input-Output LCA (EIO-LCA)



13.1. Life-Cycle Assessment (LCA): Motivation

- ▶ The IOM reflects a *snapshot* of *all products* of a national economy in the *steady state*
- ▶ Sometimes, it is more instructive or relevant to consider *the total lifetime* of a *single product* in a *time dependent way* by assessing production, operation, and destruction/recycling of this product.
- ▶ This is formalized by the methods of **Life-Cycle Assessment (LCA)** (German: **Ökobilanz**).
- ▶ However, LCA only considers first-order indirect effects, e.g., CO₂ emissions caused by electric vehicles through the CO₂ footprint of electricity production
- ▶ The class of **Econometric Input-Output (EIO) LCA models** combines both approaches.

The standard LCA procedure

1. Define the life phases of the product in question:
 - ▶ production
 - ▶ operation/usage
 - ▶ destruction/recycling.
2. For each life phase, calculate the amount of needed materials/energy resulting in the **life-cycle inventory** \tilde{y}_j for product category j (the tilde denotes that the product is given in physical units such as kg or kWh rather than in €).
3. The total emissions e_i of pollutant i during the life time is obtained using the **emission factor matrix** \mathbf{C} :

$$e_i = \sum_j C_{ij} \tilde{y}_j$$

where the emission factor C_{ij} gives the units of pollutant i caused by one unit of product j (including the production chain).

Example: Gasoline vehicle

Gasoline and Diesel vehicles are two examples of **internal combustion vehicles (ICV)**

1. Life-cycle inventory

- ▶ $\tilde{y}_1 = 800$ kg steel (900 kg at production time, 80 kg spare parts during lifetime, 20 % emission-neutral recycling contribution),
- ▶ $\tilde{y}_2 = 60$ kg aluminum (100 kg production, 40 % of it can be recycled without additional emissions)
- ▶ $\tilde{y}_3 = 100$ kg plastic
- ▶ $\tilde{y}_4 = 50$ kg rubber
- ▶ $\tilde{y}_5 = 36$ kg lead (three starter batteries à 12 kg)
- ▶ $\tilde{y}_6 = 15\,000$ l gasoline (250 000 km at 6 l/100 km during lifetime)

so we have

$$\tilde{\mathbf{y}} = (800 \text{ kg}, 60 \text{ kg}, 60 \text{ kg}, 60 \text{ kg}, 36 \text{ kg}, 15\,000 \text{ l})'$$

Example: Gasoline vehicle (ctnd)

2. Total CO₂ emissions

Defining e_1 to be the CO₂ emissions in kg (e_2 could be NO_x, e_3 PM and so on), we have

$$e_1 = \sum_{j=1}^6 C_{1j} \tilde{y}_j$$

with the row vector

$$C_{\text{CO}_2} = (C_{1j}) = (4, 30, 2, 2, 20, 2.7 \text{ kg/l}).$$

The last emission factor $C_{16} = C_{16}^{\text{w}2\text{t}} + C_{16}^{\text{t}2\text{w}}$ is the sum of two contributions:

- ▶ **Well-to-tank (w2t)** emissions of the production chain mining → transport to refinery → refining process → transport to the gas station: $C_{16}^{\text{w}2\text{t}} = 0.4 \text{ kg/l}$,
- ▶ **Tank-to-wheel (t2w)** emissions dictated by the chemistry during the actual combustion: $C_{16}^{\text{t}2\text{w}} = 2.3 \text{ kg/l}$ (it would be 2.7 kg/l for Diesel, i.e., the total w2w emissions of gasoline are about the t2w emissions when burning Diesel).

Example 2: Battery-electric vehicle (BEV)

- ▶ The **Life-cycle inventory** of steel, aluminum, rubber, plastic etc is comparable to that of the ICVs.
- ▶ The starter batteries are replaced by the Lithium driving batteries (2×300 kg) and the gasoline is replaced by the needed electrical energy, typically 20 kWh per 100 km:

$$\tilde{\mathbf{y}} = (800 \text{ kg}, 60 \text{ kg}, 60 \text{ kg}, 60 \text{ kg}, 600 \text{ kg}, 50\,000 \text{ kWh})'$$

- ▶ This leads to the new CO₂ emission factors vector

$$\mathbf{C}_{\text{CO}_2} = (4, 30, 2, 2, 20, 0.45 \text{ kg/kWh}).$$

- ▶ The Li driving batteries are expensive to produce and there is much controversy in estimating their overall emission factor C_{15}
- ▶ The energy emission factor is based, e.g., on the present (2019) German energy mix emitting 450 g CO₂ per kWh of electrical energy at the socket

Questions on LCA

- ? Is it possible to check, at a glance, whether the example BEV emits less CO₂ per km than the example ICV *when considering the driving phase alone*?
- ! Per 100 km, the BEV indirectly emits 20 kWh * 0.45 kg/kWh=9 kg. The ICV vehicle emits directly and indirectly 6 l * 2.7 kg/l=16.2 kg. So, the BEV “wins” when considering the direct and indirect emissions in the driving phase alone.
- However, the BEV production emissions are significantly higher. Furthermore, less than ideal efficiencies when charging/discharging have not been considered.
- ? How would you proceed to calculate the *break-even* mileage beyond which a BEV is more environmentally friendly (“green”) than the ICV?
- ! We saw that the *driving* emissions C' per kilometer x for the ICV are higher compared to the BEV. In contrast, it is the other way round for the *fixed* emissions C^0 due to production/disposal/recycling. So, just calculate the break-even kilometrage x_c by the equation

$$C_{\text{BEV}}^0 + C'_{\text{BEV}}x_c = C_{\text{ICV}}^0 + C'_{\text{ICV}}x_c$$

Questions on LCA (ctnd.)

- ? Give the two most important factors influencing the total LCA emissions of battery-electric vehicles.
- (i) The energy mix of the used electricity (this is tricky! particularly, you cannot save your soul by paying indulgences/ordering “green” electricity)
 - (ii) The production and disposal/recycling emissions of the battery and whether you need more than one battery during lifetime (to research this is even more tricky).
- ? A common saying states that *the Sun does not issue invoices* nor does the production of electric energy by photovoltaic (PV) elements entail any direct CO₂ emissions. Discuss why PV energy still has a nonzero CO₂ footprint and how to calculate the PV CO₂ emission factor. Use LCA arguments and assume a steady state.
- (i) Get information about the usable lifetime τ ,
 - (ii) Check the climate where you want to install your PV and determine the average power (in Germany, it is about 10% of the installed power P_{\max}) and calculate the total electric energy delivered, e.g., $W_{\text{el}} = 0.1 \tau P_{\max}$
 - (iii) Get the production and recycling emissions C of your PV including the connection to the electric grid and calculate the CO₂ footprint $e_{\text{PV}} = C/W_{\text{el}}$ [kg/kWh].

13.2. Econometric Input-Output LCA

See the [German script, Chapter 5.3](#).